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Seismic Evaluation and Retrofit of Concrete Buildings
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Executive Summary

■ Existing concrete buildings pose a great challenge in California

Concrete is popular as a building material in California. For the most part, it serves its functions well; however concrete is inherently brittle and performs poorly during earthquakes if not reinforced properly. The San Fernando Earthquake of 1971 dramatically demonstrated this characteristic. Shortly thereafter, code writers revised the design provisions for new concrete buildings to provide adequate ductility to resist strong ground shaking. There remain, nonetheless, millions of square feet of nonductile concrete buildings in California.

The consequences of neglecting this general risk are inevitably catastrophic for some individual buildings. The collapse of a single building has the potential for more loss of life than any other catastrophe in California since 1906. The potential defects in these buildings are often not readily apparent. Condemnation of all to mandatory retrofit is an unacceptable economic burden. Unfortunately, procedures to identify and to retrofit efficiently those that are vulnerable to collapse have not been available. As a part of its mandate under the California Earthquake Hazards Reduction Act of 1986, the Seismic Safety Commission is moving aggressively to meet this need by helping to develop standards for the evaluation and retrofit of existing concrete buildings with this document, *Seismic Evaluation and Retrofit of Concrete Buildings (Product 1.2/1.3)*. It contains the combined results of two contracts with the Applied Technology Council (Product 1.2 for the development of an analytical methodology and Product 1.3 for the inclusion of foundation effects).

■ The challenge spans a broad spectrum from highly technical engineering details to general issues of public policy

This document has a dual focus. On a technical level, engineers will find systematic guidance on how to investigate concrete buildings subject to seismic shaking. Depending on the specific characteristics of a particular building, they may select from an array of alternatives. These technical procedures are not alone sufficient for effective evaluation and retrofit. Owners, architects, building officials, and others must make critical decisions based on technical information coming from the engineers. Conversely, policy and management issues affect the course of the technical analysis. The recommended approach advocates a broad context for the process to expand the perspectives of all involved.

■ Multiple performance objectives are the context for defining and managing seismic risk

In *Turning Loss to Gain* (CSSC 1995) its report to Governor Wilson on the Northridge Earthquake, the Seismic Safety Commission identifies a fundamental drawback of the seismic provisions of current building codes. The seismic

performance that can be expected from a building designed in accordance with the code is not explicit. The implication is that buildings will not collapse in large earthquakes. Owners rarely recognize that this goal allows for substantial damage contributing to the potential for large capital losses and business interruption. In spite of significant improvements in codes after earthquakes in the past, their traditional approach is not conducive to effective overall management of seismic risks in California. This is particularly true of existing buildings for which codes for new buildings are effectively meaningless when it comes to seismic performance. The Commission concludes that multiple performance objectives are required to define alternatives and quantify acceptable risks.

A seismic performance objective has two essential parts—a damage state and a level of hazard. "Life safety" and "immediate occupancy" are descriptors of damage states that do not constitute performance objectives until they are associated with a specific level of seismic hazard. The hazard might be an earthquake (M7.0 on the Hayward Fault adjacent to a site) or a probability of an intensity of ground shaking (10% chance of being exceeded in 50 years). Defined in this way, a performance objective represents a specific risk. Using the new analysis procedures in this document as a technical tool, it is possible to investigate buildings for multiple performance objectives. This approach provides building owners and others a framework for informed judgments on the acceptability of various risks and the benefits of mitigative action in light of the associated costs.

■ New structural analysis procedures give engineers a more realistic picture of building performance during earthquakes

Traditional retrofit design techniques assume that buildings respond elastically to earthquakes. In reality, large earthquakes can severely damage buildings causing inelastic behavior that dissipates energy. The assumption that buildings remain elastic simplifies the engineer's work but obscures a basic understanding of actual performance. The use of traditional procedures for existing buildings can lead to erroneous conclusions on deficiencies and unnecessarily high retrofit costs. More disturbingly, they can miss important defects in some buildings. Foundations are a good example. Traditional analyses normally assume that buildings are rigid at their base, which can lead to the prediction of high forces implying extensive retrofitting measures for walls and floors. It also can underestimate the structural displacements that control damage to other parts of the structure, such as columns. In reality, foundations often are quite flexible. Rocking or yielding of the supporting soil material might reduce forces and the need to retrofit the shear walls. The foundation movements, however, also lead to larger displacements which may imply potential collapse of columns.

Relatively new analysis procedures described in this document help describe the inelastic behavior of the structural components of a building. These techniques can estimate more accurately the actual behavior of a building during a specific ground motion. The document provides extensive guidance on the use of these procedures including properties for concrete components and detailed information to incorporate foundation effects. Using this information, the engineer formulates a component model of the building structure. The analysis procedure tells how to identify which part of the building will fail first. As the load and displacement increase, other elements begin to yield and deform inelastically. The resulting graphic "curve" is an easy-to-visualize representation of the capacity of the building. Several alternative techniques allow the demand from a specific earthquake or intensity of ground shaking to be correlated with the capacity curve to generate a point on the curve where capacity and demand are equal. This "performance

point" is an estimate of the actual displacement of the building for the specified ground motion. Using this performance point, the engineer can characterize the associated damage state for the structure and compare it with the desired performance objective. This allows the engineer to pinpoint deficiencies in each building part and address them directly with retrofit measures only where necessary. In short, the procedure gives the engineer a better understanding of the seismic performance characteristics of the building and results in a more effective and cost-efficient retrofit.

■ The new technologies require extensive engineering judgment

A large team of earthquake engineering experts compiled and generated the information in this document. A panel of respected leaders in the field periodically reviewed the development as representatives of the Seismic Safety Commission. Practitioners from throughout California voiced their opinions at a series of workshops on the document. There is a consensus that the technical procedures are complex. There are several sources and implications of this complexity. The nature of the inelastic analysis itself requires a basic understanding of the principles of structural dynamics and mechanics of materials. The scope of the analysis typically requires computer-aided solutions. While most competent engineers with seismic design experience in California are capable of dealing with these issues, traditional design procedures commonly used in current practice do not demand that they do. Unfortunately, in the competitive design environment, most uninformed owners are not yet willing to pay larger fees for the more time-consuming approach. Although the benefits to owners in reduced construction costs, more reliable building performance, and reduced costs to repair damage due to future earthquakes can justify the higher fees in many cases, this has not yet been widely communicated. In the future, better communication and changes in the marketplace for engineering services could resolve this aspect of complexity.

The document provides guidance applicable to all concrete buildings. Within a general framework for evaluation and retrofit, new procedures for inelastic analysis are alternatives to simpler traditional methods for detailed analysis of some, but not all, buildings. The dividing line between buildings that can benefit from inelastic analysis and those that will not can be subtle, however. Every building has its own characteristics and often only experienced engineers can decide when traditional design methods are adequate. This necessity of experience and judgment on the part of the engineer extends beyond the selection of appropriate analysis techniques. The new inelastic procedures require many decisions on component properties and modeling techniques that involve considerable judgment. The interpretation of results must carefully include consideration of inherent uncertainties and the limitations of basic assumptions. Qualifying experience and judgment is not the exclusive domain of a select few engineers or firms. No one is capable of infallible prediction of the seismic performance of concrete buildings. The solution to this unavoidable complexity is to eliminate complete reliance on the judgment of a single engineer and, instead, rely on constructive and cooperative peer review processes. The Seismic Safety Commission, in *Turning Loss to Gain*, advocates such a change in the California Building Code to require independent peer review of complex buildings.

■ Effective and efficient seismic evaluation and retrofit of concrete buildings demand fundamental changes

The need for technical peer review is only one of the changes to conventional planning and design processes. The design engineers themselves face the challenge to develop and maintain their technical skills beyond those that they currently

use in practice. Architects must recognize the impact of seismic risk on building function and the importance of nonstructural damage to building performance. Building officials are accustomed to designs that can be easily checked against prescriptive codes and standards. They must expand or supplement their own skills and implement procedures to monitor performance-based designs. As important as these changes for design and building professionals are, they alone will do little without the demand and support of building owners for change.

The perspective of building owners is the key to progress. If a building meets the code under which it was built and there is no legal requirement to retrofit it, owners generally have been satisfied. Few understand the risks they actually face. Performance-based evaluation of buildings can give them a picture of how earthquakes impact their businesses and investments. They can then begin to make informed decisions to manage and reduce risks in a cost-efficient way. The most basic change that owners will face is the realization that they are the decision maker. Engineers can advise them on relative risks, but acceptability rests with the owner. This concept runs counter to the prevailing attitude that it is the design professional who decides on acceptable risk.

■ Product 1.2/1.3 initiates the transition with a step in the right direction

The new technical analysis procedures, coupled with performance-based evaluation and design concepts, have great promise. Realistically, their implementation and complete development will take some time. The realization of the full potential of the new approaches demands technical information and data not currently available. Significant changes to business as usual are required on the part of all involved in the evaluation and retrofit process. There are several important strategies that can enhance future progress.

California is not acting alone in pursuing effective evaluation and retrofit methodologies. In fact, many of the individuals responsible for this document are also involved on the federal initiative to develop national guidelines for the seismic rehabilitation of buildings. They initially capitalized on the federal effort by using it as a springboard for further development. In return, key enhancements from *Product 1.2/1.3* have been funneled back into the federal document. There are at least two desirable outcomes of this synergism. *Product 1.2/1.3* uses concepts and language compatible with the federal guidelines. This consistency will raise the comfort level of all involved and accelerate the implementation of the procedures. The federal government, through the Federal Emergency Management Agency and the National Science Foundation, has plans to continue the development of performance-based design aggressively. The benefit for existing concrete buildings will include improved information on the inelastic properties of both structural and nonstructural components.

The interest on the part of structural engineers in inelastic analysis procedures is very high. The Structural Engineers Association of Northern California recently sponsored a seminar on the subject and had to turn people away. Future sessions are planned and interest probably will spread through the larger state organization. Focused sessions are required for geotechnical and structural engineers. The importance of foundation effects on the seismic performance of some buildings requires greater communication and cooperation. Training sessions are also essential for building officials throughout California. This document is a natural curriculum for these efforts and the Seismic Safety Commission encourages its use.

A concerted effort to educate building owners on effective seismic risk management is essential. First of all, the benefits of the new procedures need to be documented with extended example building studies. The proposed procedures have been used successfully by others and their stories

need to be told. Side by side comparison of the results of the proposed procedures with those of traditional methods including retrofit costs would quantify the differences. State agencies are a natural starting point for workshops and seminars aimed at the management level. These could be expanded to the private sector through organizations such as the Building Owners and Managers Association. This initiative to engage building owners has not yet been implemented in any effective program.

Finally, this document needs to be continually updated to reflect advancement in the state of the art and the valuable lessons from practical application. A repository of information should be established to allow users to submit suggestions and share experiences on evaluation and retrofit projects.

The Seismic Safety Commission is confident that California can meet the challenge of concrete buildings with improved understanding and information. *Product 1.2/1.3* provides the basis for improved understanding of the actual behavior of structures for realistic earthquakes and for informed management of seismic risks. With continued vigilant effort on the part of design professionals, building officials, and owners to enhance the process, the risks to safety and economy posed by earthquakes can be steadily reduced to acceptable levels.